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(54) **VERTICAL-CAVITY SURFACE-EMITTING LASER DIODE AND OPTICAL TRANSMISSION APPARATUS**

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　　See application file for complete search history.

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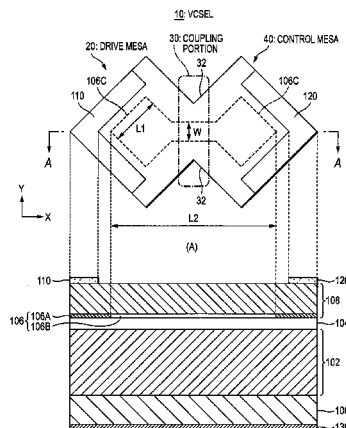*Primary Examiner* — Jessica Stultz
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(57)　　**ABSTRACT**

A vertical-cavity surface-emitting laser diode includes: a first resonator that has a plurality of semiconductor layers comprising a first current narrowing structure having a first conductive region and a first non-conductor region; a first electrode that supplies electric power to drive the first resonator; a second resonator that has a plurality of semiconductor layers comprising a second current narrowing structure having a second conductive region and a second non-conductive region and that is formed side by side with the first resonator, the second current narrowing structure being formed in same current narrowing layer as the layer where the first current narrowing structure is formed; and a coupling portion as defined herein; and an equivalent refractive index of the coupling portion is smaller than an equivalent refractive index of each of the first resonator and the second resonator.
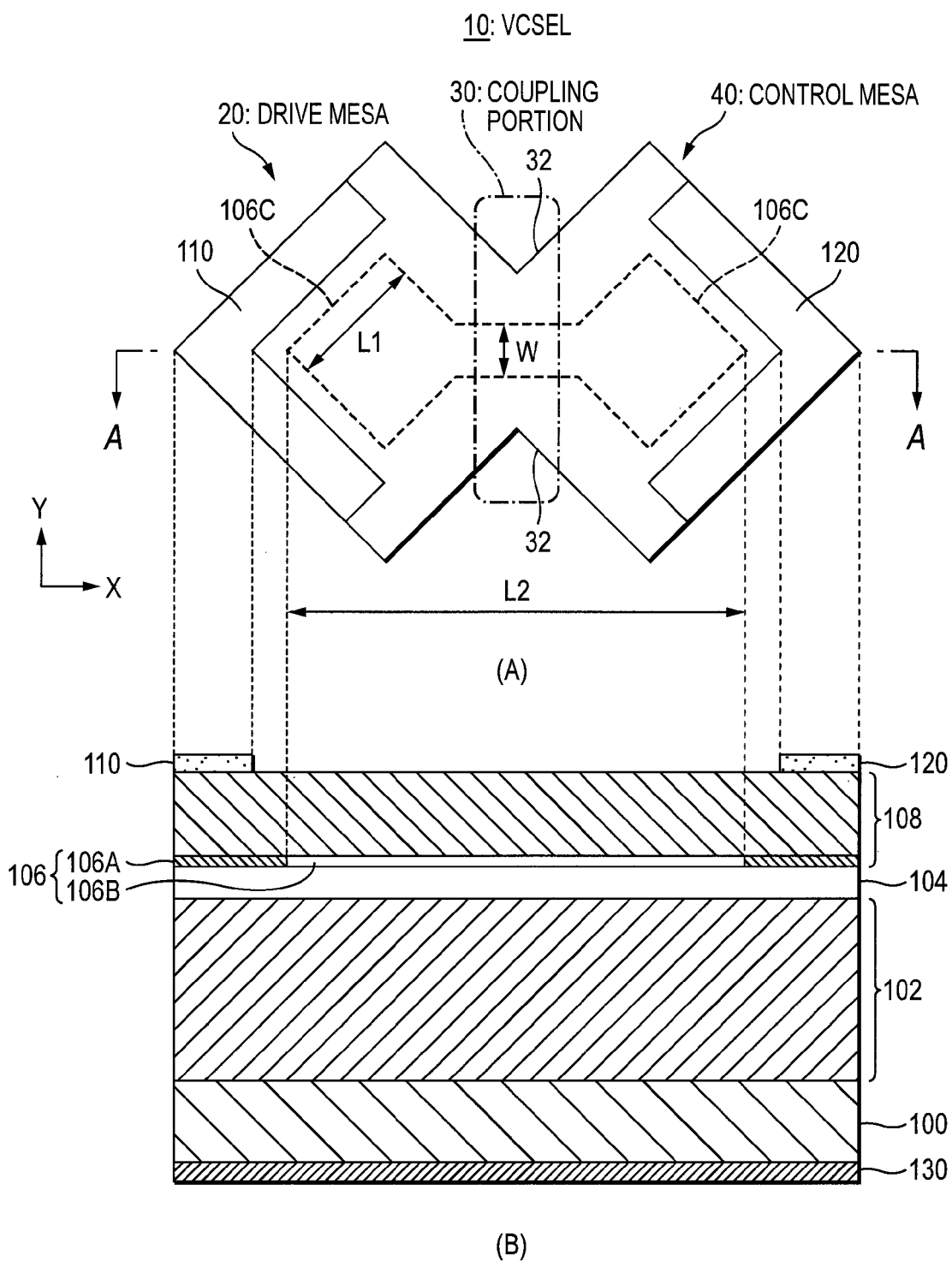
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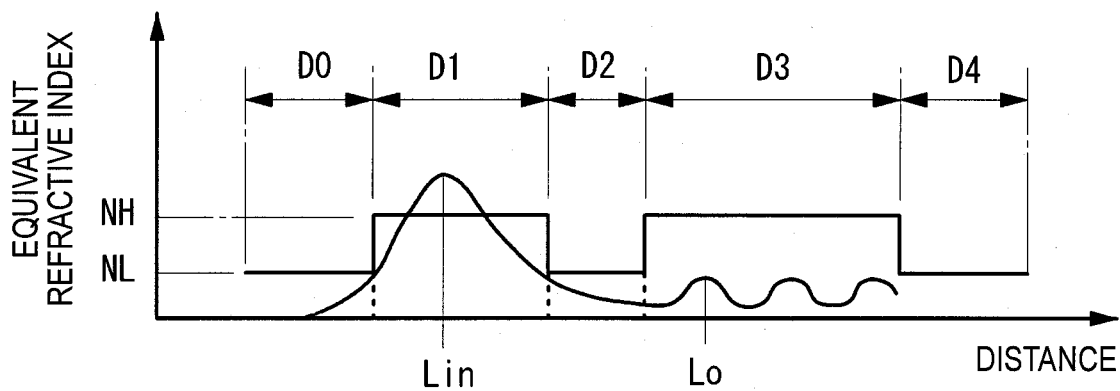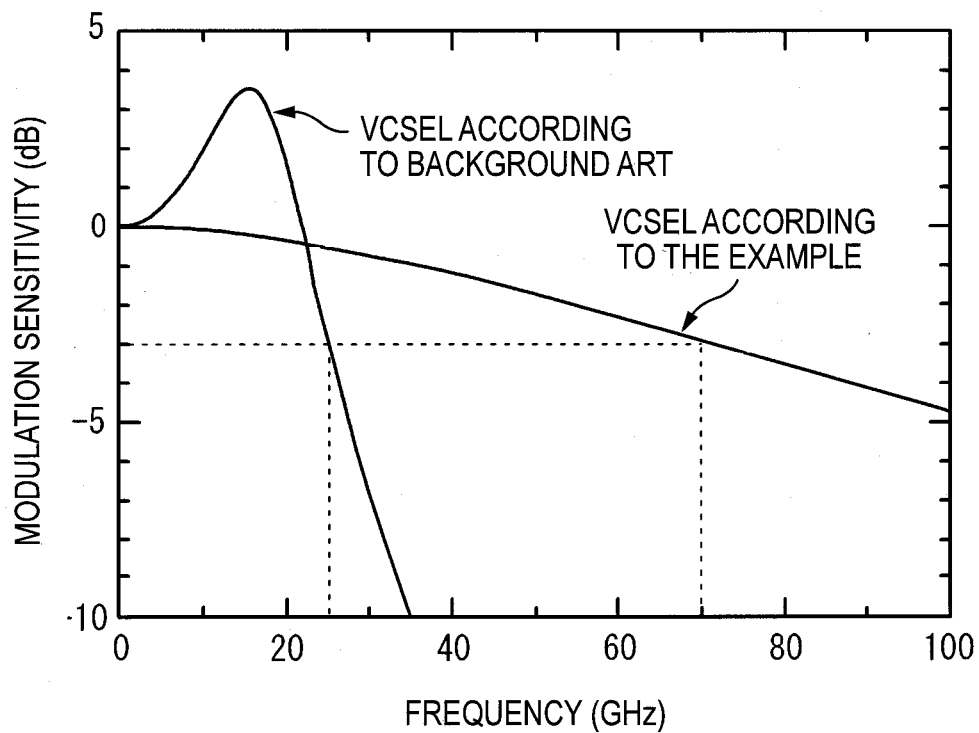
FIG. 1

10: VCSEL

30: COUPLING
PORTION

20: DRIVE MESA

40: CONTROL MESA

32

106C

106C

110

120

L1

W

A

A

Y

X

32

L2

(A)

110

120

108

106 { 106A
106B

104

102

100

130

(B)

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

DELAY TIME: 1ps, 2ps, 2.4ps, 3ps, 5ps, 10ps

FIG. 7

10A: VCSEL

20: DRIVE MESA   30: COUPLING PORTION   40: CONTROL MESA

200

106C   106C

110   120

A ← → A

Y
↑
└→ X

(A)

200

110   120
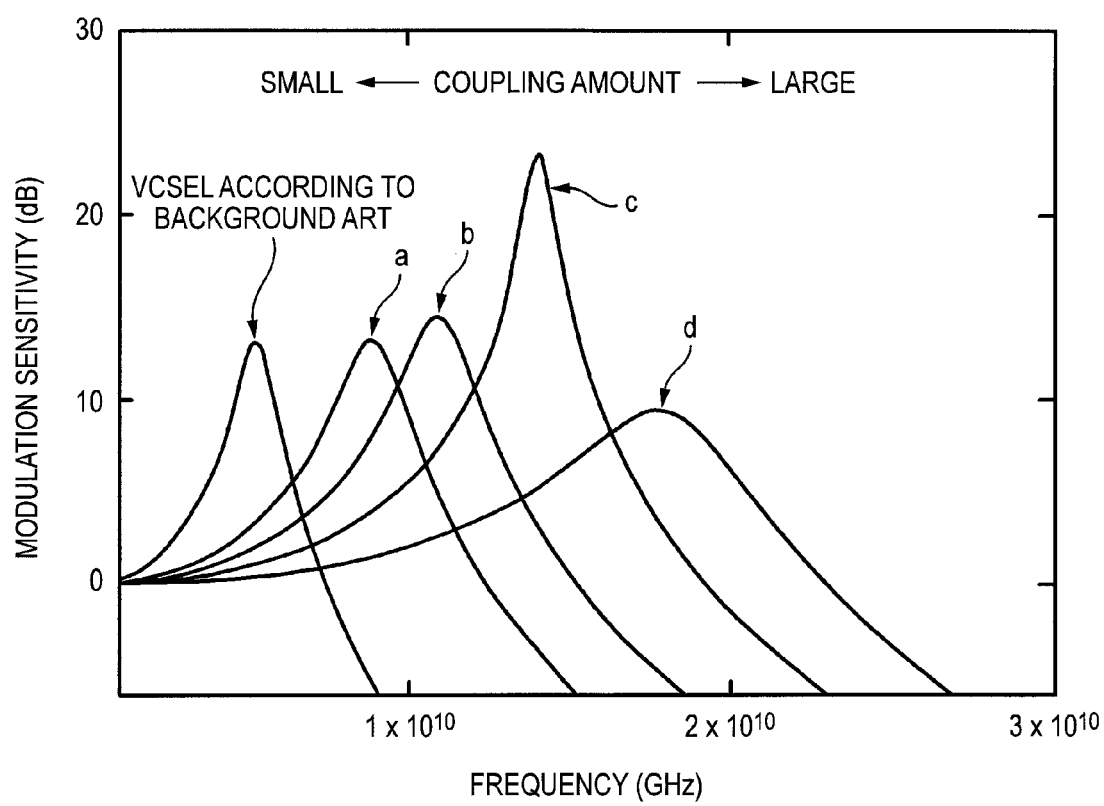
108

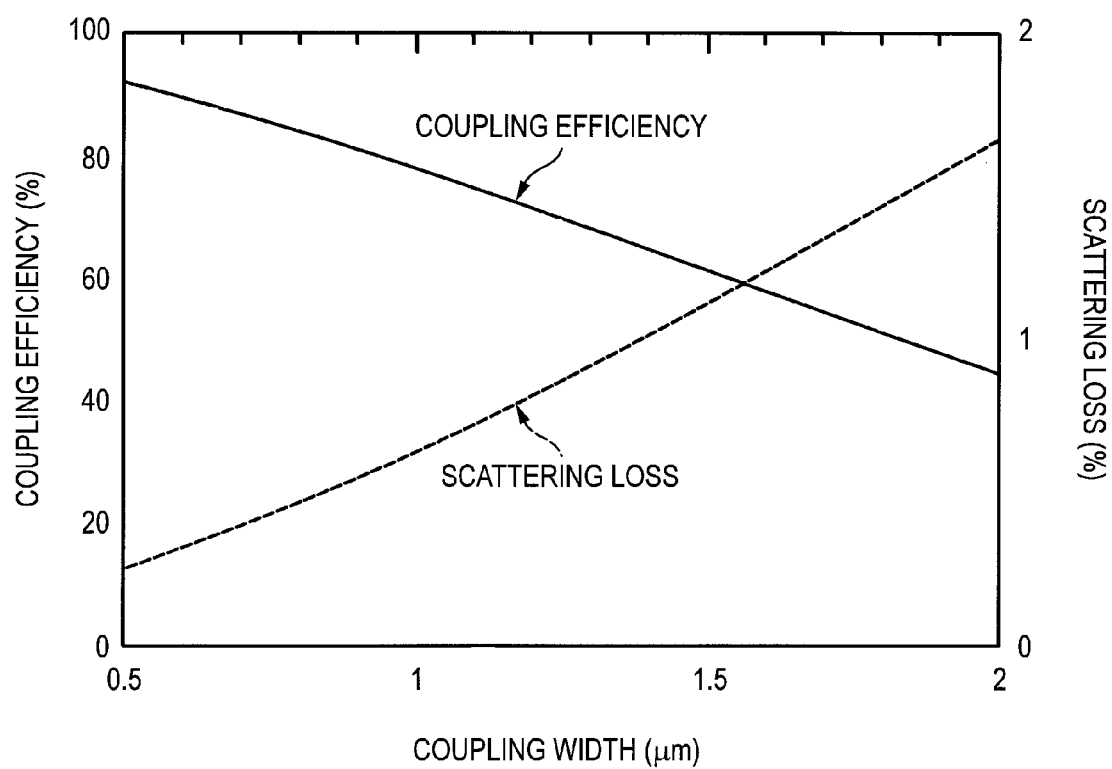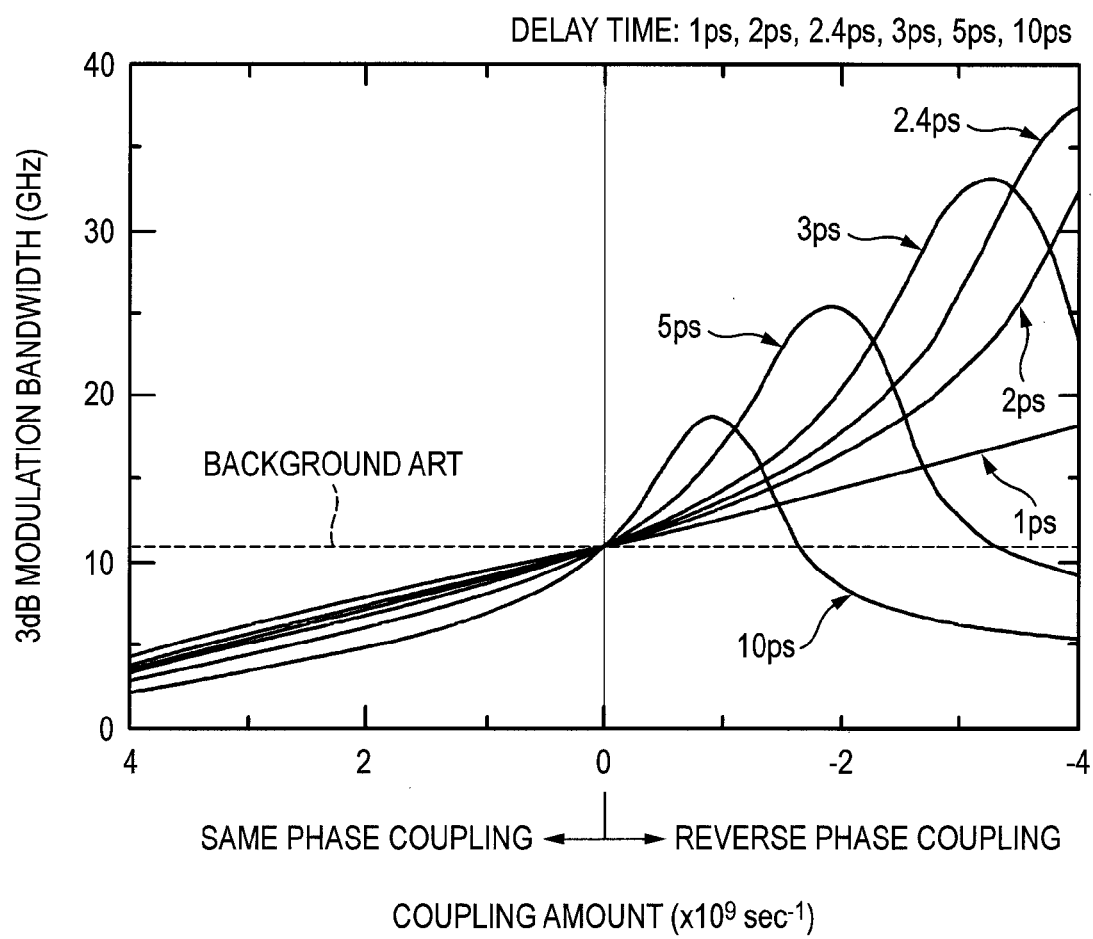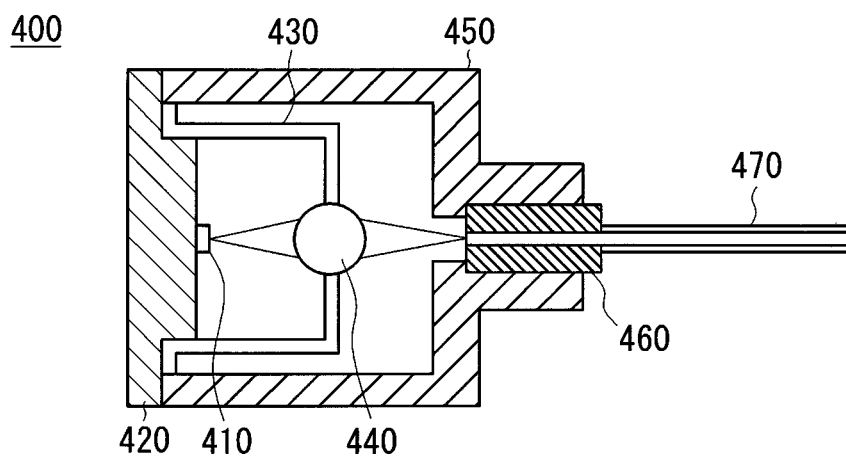106 { 106A / 106B   104

102

100

130

(B)

FIG. 8

FIG. 9

VERTICAL-CAVITY SURFACE-EMITTING LASER DIODE AND OPTICAL TRANSMISSION APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based on and claims priority under 35 USC 119 from Japanese Patent Application No. 2013-163757 filed on Aug. 7, 2013.

BACKGROUND

1. Technical Field

The present invention relates to a vertical-cavity surface-emitting laser diode and an optical transmission apparatus.

2. Related Art

Recently, a light source capable of providing transmission at a high rate up to about 100 Gb/s with low power consumption is required with the accelerated increase of optical link transmission capacity. In order to use a vertical-cavity surface-emitting laser diode as such a light source, the modulation rate of the vertical-cavity surface-emitting laser diode must be further increased.

SUMMARY

According to an aspect of the invention, there is provided a vertical-cavity surface-emitting laser diode including: a first resonator which has a plurality of semiconductor layers including a first current narrowing structure having a first conductive region and a first non-conductor region; a first electrode which supplies electric power to drive the first resonator; a second resonator which has a plurality of semiconductor layers including a second current narrowing structure having a second conductive region and a second non-conductive region and which is formed side by side with the first resonator, the second current narrowing structure being formed in the same current narrowing layer as the layer where the first current narrowing structure is formed; and a coupling portion which couples the plurality of semiconductor layers in the first resonator with the plurality of semiconductor layers in the second resonator respectively; wherein: the equivalent refractive index of the coupling portion is smaller than the equivalent refractive index of each of the first resonator and the second resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the present invention will be described in detail based on the following figures, wherein:

FIG. 1 is a schematic plan view of a vertical-cavity surface-emitting laser diode according to a first Example of the invention and a sectional view of the same vertical-cavity surface-emitting laser diode taken along the line A-A of the plan view;

FIG. 2 is a view showing an equivalent refractive index and a light confinement distribution of the vertical-cavity surface-emitting laser diode according to the first Example of the invention;

FIG. 3 is a graph showing frequency response characteristic of the vertical-cavity surface-emitting laser diode according to the first Example of the invention;

FIG. 4 is a graph showing the relation between coupling efficiency and modulation sensitivity of the vertical-cavity surface-emitting laser diode according to the first Example of the invention;

FIG. 5 is a graph showing the relation among a coupling width, coupling efficiency and scattering loss of the vertical-cavity surface-emitting laser diode according to the first Example of the invention;

FIG. 6 is a graph showing the relation between a delay time and a modulation bandwidth of the vertical-cavity surface-emitting laser diode according to the first Example of the invention and the relation between reverse phase coupling and same phase coupling and the modulation bandwidth;

FIG. 7 is a schematic plan view of a vertical-cavity surface-emitting laser diode according to a second Example of the invention and a sectional view of the same vertical-cavity surface-emitting laser diode taken along the line A-A of the plan view;

FIG. 8 is a schematic plan view of a vertical-cavity surface-emitting laser diode according to a third Example of the invention and a sectional view of the same vertical-cavity surface-emitting laser diode taken along the line A-A of the plan view; and

FIG. 9 is a sectional view showing one example of the aspect of an optical transmission apparatus using the vertical-cavity surface-emitting laser diode according to any one of these Examples of the invention.

REFERENCE SIGNS LIST

10: VCSEL
20: drive mesa
30: coupling portion
32: constricted shape
40: control mesa
100: GaAs substrate
102: lower DBR
104: active region
106: current narrowing layer
106A: oxidized region
106B: non-oxidized region
106C: boundary
108: upper DBR
110: drive electrode
120, **122**: control electrode
130: n-side electrode
200: insulated region

DETAILED DESCRIPTION

VCSELs (Vertical-Cavity Surface-Emitting Laser diode, hereinafter referred to as VCSEL) according to exemplary embodiments of the invention will be described below with reference to the drawings. In addition, the scale in each drawing is emphasized in order to make it easy to understand features of the invention. Accordingly, it should be noted that the scale in each drawing is not always identical to the scale of a real device.

FIG. 1 includes a schematic plan view of a VCSEL according to a first Example of the invention and a sectional view of the same VCSEL taken along the line A-A of the plan view. As shown in (A) of FIG. 1, the VCSEL 10 according to the Example is configured to include a first columnar structure 20, a coupling portion 30 and a second columnar structure 40 which are formed monolithically on a substrate. The first columnar structure 20 and the second columnar structure 40 are disposed in an X direction. The first columnar structure 20 is coupled to the second columnar structure 40 by the coupling portion 30. The first columnar structure 20 serves as a drive mesa and includes a first resonator. The second columnar structure 40 serves as a control mesa and includes a

second resonator. The coupling portion **30** includes semiconductor layers shared with the first columnar structure **20** and the second columnar structure **40**. The coupling portion **30** at least optically couples the first columnar structure **20** and the second columnar structure **40** to each other. In a preferable mode, the coupling portion **30** serves for propagating a part of light generated by the first columnar structure **20** toward the second columnar structure **40** and feeding the light reflected on the second columnar structure **40** back to the first columnar structure portion **20**.

In (A) of FIG. **1**, the first and second columnar structures **20** and **40** are formed substantially symmetrically in the X direction with respect to the coupling portion **30** and the first and second columnar structures **20** and **40** are formed into rectangular shapes in plan view. This is simply an example. The first and second columnar structures **20** and **40** are not necessarily symmetric. The first and second columnar structures **20** and **40** are not limited to the rectangular shapes. Alternatively, the first and second columnar structures may be cylindrical structures or columnar structures formed into elliptical shapes in plan view. The first and second columnar structures may be formed into asymmetric shapes. Further, the first and second columnar structures may have different shapes and different sizes from each other. Incidentally, in the following description, the first columnar structure **20** will be referred to as drive mesa and the second columnar structure **40** will be referred to as control mesa for convenience's sake.

As shown in (B) of FIG. **1**, the laminate structure of the VCSEL **10** is the same as a typical 980-nm InGaAs/GaAs triple quantum well structure. That is, the laminate structure of the VCSEL **10** is formed out of a laminate of an n-type lower distributed bragg reflector **102** (hereinafter referred to as DBR), an active region **104** and a p-type upper DBR **108** on an n-type GaAs substrate **100**. The n-type lower DBR **102** has AlGaAs layers with different Al compositions stacked alternately. The active region **104** is formed on the lower DBR **102** and includes a quantum well layer interposed between an upper spacer layer and a lower spacer layer. The p-type upper DBR **108** is formed on the active region **104** and has AlGaAs layers with different Al compositions stacked alternately. The n-type lower DBR **102** has a laminate of high refractive index layers and low refractive index layers, such as a laminate of plural pairs of $Al_{0.92}Ga_{0.08}As$ layers and $Al_{0.16}Ga_{0.84}As$ layers. The thickness of each of these layers is $\lambda/4n_r$ (λ designates an oscillation wavelength and n_r designates the refractive index of a medium). These layers are stacked alternately by 40 cycles. The carrier concentration after silicon as an n-type impurity is doped is, for example, 3×10^{18} cm^{-3}.

In the active region **104**, the lower spacer layer consists of an undoped $Al_{0.3}Ga_{0.7}As$ layer, the quantum well active layer consists of an undoped $In_{0.2}Ga_{0.8}As$ quantum well layer and an undoped GaAs barrier layer, and the upper space layer consists of an undoped $Al_{0.3}Ga_{0.7}As$ layer.

The p-type upper DBR **108** has a laminate of high refractive index layers and low refractive index layers, such as a laminate of plural pairs of $Al_{0.92}Ga_{0.08}As$ layers and $Al_{0.16}Ga_{0.84}As$ layers. The thickness of each of these layers is $\lambda/4n_r$. These layers are stacked alternately by 25 cycles. The carrier concentration after carbon as a p-type impurity is doped is, for example, 3×10^{18} cm^{-3}. A current narrowing layer **106** consisting of a p-type $Al_{0.98}Ga_{0.02}As$ layer (or AlAs layer) is formed on or inside the lowermost layer of the upper DBR **108**. In addition, a contact layer (for example, 1×10^{19} cm^{-3}) made of p-type GaAs with a high concentration of impurities may be formed on the uppermost layer of the upper DBR **108**.

The current narrowing layer **106** has a higher Al composition than that of each of the lower DBR **102** and the upper DBR **108** so that oxidization in the current narrowing layer **106** can be accelerated in a mesa oxidization process. When the mesas shown in (A) of FIG. **1** are oxidized, oxidized regions **106A** (indicated as hatched portions in (B) of FIG. **1**) oxidized selectively are formed inward from side walls of the drive mesa **20**, the coupling portion **30** and the control mesa **40** so as to form a current narrowing structure. When oxidization proceeds inward at a substantially constant speed, the planar shapes of non-oxidized regions **106B** are formed into shapes in which the planar shapes of the mesas **20** and **40** are substantially reflected respectively. The non-oxidized regions **106B** are surrounded by the oxidized regions **106A**. A broken line **106C** in (A) of FIG. **1** schematically designates a boundary between the oxidized regions **106A** and the non-oxidized regions **106B**. The refractive index of the $Al_{0.98}Ga_{0.02}As$ layer (or AlAs layer) constituting the current narrowing layer **106** is about 3.0. However, when the $Al_{0.98}Ga_{0.02}As$ layer is oxidized, the refractive index of the $Al_{0.98}Ga_{0.02}As$ layer is reduced to be about 1.7. Thus, transverse light is confined in the non-oxidized regions **106B** surrounded by the oxidized regions **106A**. In addition, since the oxidized regions **106A** have high electric resistance, the oxidized regions **106A** substantially serve as non-conductive regions. Carriers injected from an electrode are confined in the non-oxidized regions **106B** serving as conductive regions. Thus, the current and the light can be confined in the non-oxidized regions **106B** due to the current narrowing structure.

The VCSEL **10** according to the Example includes the coupling portion **30** between the drive mesa **20** and the control mesa **40**. The coupling portion **30** couples the semiconductor layers of the lower DBR **102**, the active region **104** and the upper DBR **108** in the drive mesa **20** with the corresponding semiconductor layers of the lower DBR **102**, the active region **104** and the upper DBR **108** in the control mesa **40** respectively. The coupling portion **30** includes an oxidized region **106A** and a non-oxidized region **106B** for coupling the oxidized region **106A** and the non-oxidized region **106B** in the drive mesa **20** with the oxidized region **106A** and the non-oxidized region **106B** in the control mesa **40** respectively. Thus, the drive mesa **20** and the control mesa **40** are coupled optically. In addition, the coupling portion **30** serves for propagating a part of light generated by the drive mesa **20** toward the control mesa **40** and feeding the light reflected on the control mesa **40** back to the drive mesa **20**. Accordingly, the equivalent refractive index of the coupling portion **30** is designed to be smaller than the equivalent refractive index of the non-oxidized region **106B** in each of the drive mesa **20** and the control mesa **40**. The equivalent refractive index used herein designates an effective refractive index of semiconductor multilayer films with different refractive indices laminated vertically on the substrate (the refractive indices of the multilayer films are regarded as the refractive index of a single layer), the effective refractive index being obtained by an equivalent refractive index method. The "equivalent refractive index" is also called as "effective index".

In the example shown in (A) of FIG. **1**, the coupling portion **30** according to the Example is processed into a constricted shape **32** whose opposite side surfaces are inclined inward to be narrow in a Y direction. Since the current narrowing layer **106** is oxidized from the side surfaces of the constricted shape **32**, the Y-direction width W of the non-oxidized region **106B** in the coupling portion **30** is made narrower than the Y-direction width W of the non-oxidized region **106B** in each of the drive mesa **20** and the control mesa **40**. In this manner, the equivalent refractive index of the coupling portion **30** is con-

trolled to be smaller than the equivalent refractive index of each of the drive mesa 20 and the control mesa 40. Incidentally, the shape and the size of the coupling portion 30 may be selected desirably. When the shape and the size of the coupling portion 30 are selected suitably, the Y-direction width of the non-oxidized region 106B in the coupling portion 30 can be actually made narrower than the Y-direction width of the non-oxidized region 106B in each of the drive mesa 20 and the control mesa 40 to thereby obtain a desired equivalent refractive index. Incidentally, the Y-direction width of the non-oxidized region 106B in the coupling portion 30 may be zero. That is, the non-oxidized region 106B of the drive mesa 20 and the non-oxidized region 106B of the control mesa 40 may be disconnected from each other. In addition, the Y-direction width W of the non-oxidized region 106B in the coupling portion 30 is a factor for determining a coupling amount or coupling efficiency between the drive mesa 20 and the control mesa 40 as will be described later.

P-side electrodes 110 and 120 made of metal and coupled to the resonator of the drive mesa 20 and the resonator of the control mesa 40 independently and respectively are formed on the upper DBR 108. The p-side electrodes 110 and 120 are made of metal such as Au or a laminate of Au/Zn/Au, etc. The p-side electrode 110 is formed into a "V"-shape to extend along two sides of the drive mesa 20 to be thereby electrically connected to the upper DBR 108. In a preferable mode, the p-side electrode 110 is formed in a position not to overlap with the non-oxidized region 106B. In other words, the p-side electrode 110 is formed in a region not to extend beyond the boundary 106C between the oxidized region 106A and the non-oxidized region 106B. Similarly, the p-side electrode 120 is formed into a "V"-shape to extend along two sides of the control mesa 40 to be thereby electrically connected to the upper DBR 108. The p-side electrode 120 is also formed in a region not to extend beyond the boundary 106C between the oxidized region 106A and the non-oxidized region 106B. In addition, an n-side electrode 130 shared by the drive mesa 20 and the control mesa 40 is formed on the back surface of the substrate 100.

The p-side electrode 110 is a drive electrode for driving the drive mesa 20 (hereinafter the p-side electrode 110 will be referred to as drive electrode). The other p-side electrode 120 is a control electrode for controlling the optical feedback of the control mesa (hereinafter the p-side electrode 120 will be referred to as control electrode). In the example in FIG. 1, the drive electrode 110 and the control electrode 120 are formed on the opposite ends of the mesas 20 and 40 respectively. However, the invention is not limited thereto. For example, as long as the VCSEL 10 according to the Example can achieve higher speed than a background-art VCSEL, the drive electrode 110 and the control electrode 120 may be formed in places other than the opposite ends.

The VCSEL 10 in the Example has a coupled resonator structure in which the drive mesa 20 having the drive electrode 110 formed therein and the control mesa 40 having the control electrode 120 formed therein are coupled to each other through the coupling portion 30 having the constricted shape, as described above. Although the rectangular coupled resonators having the same shape are shown in the Example, rectangular coupled resonators having different sizes may be used or coupled resonators having circular shapes other than the rectangular shapes may be used. The length L1 of one side of the non-oxidized region 106B formed in each of the drive mesa 20 and the control mesa 40 is, for example, 8.5 μm. The length L2 of a longer axis of the non-oxidized regions 106B formed in the coupled resonators is, for example, 28 μm. The lengths L1 and L2 of the non-oxidized regions may be made

smaller or larger than the aforementioned values in accordance with design. When light in a fundamental transverse mode is emitted from the drive mesa 20, the length L1 may be further reduced.

Thus, the drive mesa 20 and the control mesa 40 having the two vertical resonator structures are formed on the substrate. When a drive signal of a forward bias is applied between the drive electrode 110 and the n-side electrode 130, laser light is emitted from the surface of the upper DBR 108 of the drive mesa 20 vertically to the substrate. The drive signal may be a steady signal for emitting laser light continuously or may be a pulse-like signal for modulating the laser light. In addition, in the Example, it is not always necessary to apply a drive signal to the control electrode 120 of the control mesa 40. In a certain mode, a drive signal of a forward bias not smaller than a threshold which can cause laser oscillation may be applied to the control electrode 120 so that high-rate modulation of the VCSEL 10 can be improved more greatly. Since the drive signal is applied to the control electrode 120, light propagated through the control mesa 40 can be amplified and the phase of the light can be controlled. Thus, the phase of the light optically fed back from the control mesa 40 can be controlled to be a reverse phase. Due to the optical feedback in the reverse phase, the modulation frequency of the drive mesa 20 can be further increased, as will be described later.

Here, the forward bias means a positive voltage applied to the p-type semiconductor layer inside the laser diode and a negative voltage applied to the n-type semiconductor layer. A backward bias means a negative voltage applied to the p-type semiconductor layer inside the laser diode and a positive voltage applied to the n-type semiconductor layer. Incidentally, the negative voltage includes a ground potential (GND).

FIG. 2 shows the relation between the equivalent refractive index and the light confinement distribution of the VCSEL. In FIG. 2, the stepwise line designates the equivalent refractive index and the curve designates the light confinement distribution. A region D0 of a low equivalent refractive index NL corresponds to the oxidized region 106A of the drive mesa 20. A region D1 of a high equivalent refractive index NH corresponds to the non-oxidized region 106B of the drive mesa 20 in the same manner as the region D0. A region D2 of the low equivalent refractive index NL corresponds to a resonator coupling portion constituted by the coupling portion 30. A region D3 of the high equivalent refractive index NH corresponds to the non-oxidized region 106B of the control mesa 40. A region D4 of the low equivalent refractive index NL corresponds to the oxidized region 106A of the control mesa 40.

Most of light Lin generated by the resonator of the drive mesa 20 is confined in the region D1 which is the non-oxidized region 106B. However, since the regions D0, D1, D2, D3 and D4 having high and low equivalent refractive indices are formed continuously, the region D2 of the coupling portion 30 for coupling the two resonators does not completely confine the light Lin in the region D1 but guides a part of the light in the skirt of the region D1 to the control mesa 40. Even when the laser light is resonated vertically in the drive mesa 20, the laser light includes light having a slight inclination angle with respect to the vertical direction. Therefore, a part of light in the skirt is guided to the region D3 of the high equivalent refractive index through the region D2 of the low equivalent refractive index. In the state in which light Lo guided to the control mesa 40 is confined in the control mesa 40, the light Lo is propagated in a horizontal direction while being resonated inside the vertical resonator in a direction of the inclination angle. Accordingly, the propagation time of the light is slower than that of light propagated linearly in the

horizontal direction. The light propagated in the horizontal direction while being resonated inside the vertical resonator in the direction of the inclination angle is referred to as slow light.

The slow light is propagated horizontally in the non-oxidized region 106B of the control mesa 40 and then reflected on a light reflection portion provided in an end portion of the non-oxidized region 106B of the control mesa 40. In the Example, the light reflection portion uses the change of the equivalent refractive index. That is, the light is reflected on the boundary 106C between the oxidized region 106A and the non-oxidized region 106B of the control mesa 40. The light reflected on the control mesa 40 is fed back (optically fed back) again to the original resonator of the drive mesa 20 through the coupling portion 30. Incidentally, the light reflection portion is not necessarily limited to the one using the change of the equivalent refractive index. A separate light reflection member may be also attached to an end portion of the control mesa 40.

The slow light travels while being reflected between the lower DBR 102 and the upper DBR 108. Therefore, even when a horizontal distance D3 is small, the distance (the length of an optical path) with which the light actually travels corresponds to several hundred times as long as the distance D3. Accordingly, the propagation time T of the light reflected on the light reflection portion and travelling back and forth inside the slow light portion has the same effect as if the speed of the light has been delayed. In a preferable mode, the length of the optical path or the distance D3 is adjusted so that the light incident on the light reflection portion and the light reflected on the light reflection portion can be set in a reverse phase relation with each other, more preferably, in a reverse phase relation of 180° with each other.

FIG. 3 shows calculation results of frequency characteristics of the VCSEL having the background-art structure and the VCSEL according to the Example. In FIG. 3, the abscissa designates frequency (GHz) and the ordinate designates modulation sensitivity (dB). Assume that the signal intensity is allowed to decrease up to −3 dB. In this case, the frequency of the VCSEL having the background-art structure in which the control mesa is not coupled is about 25 GHz whereas the frequency of the VCSEL according to the Example is about 70 GHz. Accordingly, it is proved that 3 dB frequency is improved remarkably in the VCSEL 10 according to the Example, in comparison with that in the VCSEL having the background-art structure. The graph of FIG. 3 shows the calculation made when the light is fed back with a reverse phase. When the simulation in which the light is fed back with a reverse phase is compared with another simulation in which the light is fed back with the same phase, the result obtained in the case with the reverse phase is more preferable than the result obtained in the case with the same phase in terms of improvement of the 3 dB frequency. Further, the bandwidth of the 3 dB frequency can be improved also by control of a gain based on injection of the current from the control electrode 120. However, an effect of improvement in the bandwidth can be obtained even in the case where no current is injected from the control electrode 120.

FIG. 4 shows the change of the bandwidth in the VCSEL due to the coupling amount of the two resonators of the drive mesa and the control mesa. The coupling amount mainly depends on the distance between the drive mesa 20 and the control mesa 40 and the oxidization control of the coupling portion 30. The coupling amount (coupling efficiency) tends to be smaller when the width W of the non-oxidized region 106B in the coupling portion 30 is larger. In FIG. 4, the bandwidth in a VCSEL having no coupling, i.e. the band-

width in the background-art VCSEL is indicated as the leftmost curve, and the 3 dB bandwidth is a little less than 10 GHz. It can be confirmed that when the coupling amount is increased in the order of curves a, b, c, and d (that is, when the width W of the coupling portion 30 is reduced), the bandwidth of the modulation sensitivity extends on the high frequency side. The coupling amount is a function of the width W. Accordingly, the coupling amount can be controlled when the oxidization of the coupling portion 30 is controlled. That is, when the shape, the size, etc. of the coupling portion 30 are selected, a desired coupling amount can be obtained.

FIG. 5 shows the relation among the width W of the non-oxidized region in the coupling portion between the two mesas (i.e. the drive mesa and the control mesa), the coupling efficiency (coupling amount) and the scattering loss. As the width W of the coupling portion 30 increases, the scattering loss (broken line in FIG. 5) increases but the coupling efficiency (solid line in FIG. 5) decreases. Since the width W of the coupling portion 30 can be controlled by the distance between the two mesas 20 and 40 and the oxidization narrowing amount of the coupling portion 30 as described above, the coupling portion 30 can be designed suitably to obtain a desired high frequency characteristic by experiments or simulations. Thus, the bandwidth in the VCSEL 10 can be improved.

FIG. 6 shows the relation between the coupling amount and the 3 dB modulation bandwidth based on the delay time of the optical feedback. The region where the coupling amount is plus corresponds to the case where the optical feedback is performed with the same phase, and the region where the coupling amount is minus corresponds to the case where the optical feedback is performed with a reverse phase. In the VCSEL having the background-art structure without the optical feedback, the 3 dB modulation bandwidth is constant (broken line at about 11 GHz) regardless of the delay time. On the other hand, the illustrated relation is established between the delay time and the 3 dB modulation bandwidth when the control mesa 40 is coupled to perform the optical feedback as in the VCSEL according to the Example. Here is shown, by way of example, each 3 dB modulation bandwidth in which the delay time of the optical feedback is 1 ps, 2 ps, 2.4 ps, 3 ps, 5 ps or 10 ps. The delay time depends on the length of the optical path of the slow light travelling through the control mesa 40, that is, the delay time can be controlled based on the length of the region D3 of the non-oxidized region 106B of the control mesa 40 where the slow light is propagated, as shown in FIG. 2. Particularly in the case of the reverse phase coupling, the 3 dB modulation bandwidth is improved in any delay time. For example, when a delay of about 3 picoseconds is generated in a reverse phase, the 3 dB modulation bandwidth can be improved to about three times as large as that in the VCSEL having the background-art structure.

Thus, in order to improve the 3 dB modulation bandwidth, the optical feedback is set preferably at a reverse phase, most preferably at a reverse phase of 180°. In a first method for setting the optical feedback at a reverse phase, the length of the region D3 of the control mesa 40 is controlled to select an optimal length of the optical path as described above. In a second method, an optimal current is injected from the control electrode 120 of the control mesa 40 to thereby control the phase of light. It is a matter of course that the reverse phase of light optically fed back may be controlled by combination of the first and second methods.

Next, a second Example of the invention will be described. FIG. 7 includes a schematic plan view of a VCSEL according to the second Example and a sectional view of the same VCSEL taken along the line A-A of the plan view. The dif-

ferent point from the VCSEL **10** according to the first Example shown in FIG. **1** is a point that the VCSEL **10A** according to the second Example has an insulation structure in which a coupling portion **30** between the drive mesa **20** and the control mesa **40** is electrically insulated. In the drawings, the same constituents as those of the VCSEL shown in FIG. **1** are referred to by the same signs correspondingly, and description thereof will be omitted.

As shown in FIG. **7**, an insulated region **200** having high electric resistance is formed in the coupling portion **30** of the VCSEL **10A**. In a preferable mode, a mask pattern for exposing the coupling portion **30** is formed on the upper DBR **108** by a well-known photolithography process and ion injection of protons etc. is performed through the mask pattern so that the insulated region **200** can be formed in the coupling portion **30**. In a preferable mode, the energy of the ion injection is controlled so that the entire depth of the p-type upper DBR **108** inside the coupling portion **30** can be insulated. Incidentally, it will go well as long as the insulated region **200** is insulated at least partially on the emission surface side of an active region **104**. In a preferable mode, the insulated region **200** is formed all over the range of the coupling portion **30** in the Y direction. However, the insulated region **200** may be formed in a part of the range in the Y direction. In addition, the width of the insulated region **200** in the X direction may be selected desirably.

In the Example, the insulated region **200** is formed in the coupling portion **30** to make a structure in which carriers are prevented from being injected into the coupling portion **30** from the drive electrode **110** or the control electrode **120**, so that the decrease of the gain can be suppressed. Further, the scattering loss can be also increased. Accuracy in controlling the optical feedback with the reverse phase can be improved. In addition, in the Example, a certain degree of improvement of the 3 dB modulation bandwidth can be achieved even when no current is injected from the control electrode **120**. Incidentally, although the insulated region **200** is formed by ion injection, the insulated region **200** may be formed by another method than ion injection. For example, a groove may be formed in a part or the whole of the upper DBR **108** to thereby provide a function equivalent to the insulated region **200**.

Next, a third Example of the invention will be described. FIG. **8** includes a schematic plan view of a VCSEL **10B** according to the third Example and a sectional view of the VCSEL **10B** taken along the line A-A of the plan view. In the VCSEL according to each of the first and second Examples, light is also emitted from the control mesa **40** whereas the VCSEL **10B** according to the third Example has a structure in which light emission from the control mesa **40** is suppressed. In FIG. **8**, constituents the same as those in the VCSEL shown in FIG. **7** will be referred to by the same signs correspondingly, and description thereof will be omitted.

When light is emitted from two places in the drive mesa **20** and the control mesa **40** respectively due to light emission from the control mesa **40**, it is difficult to control the optical mode of the emitted light. Therefore, in the VCSEL **10B** according to the Example, a control electrode **122** is formed on the upper DBR **108** to cover the non-oxidized region **106B** of the control mesa **40** as shown in FIG. **8** (the control electrode **122** is indicated as a hatched portion in order to make it easy to identify the control electrode **122** in (A) of FIG. **8**). In the example shown in FIG. **8**, the coupling portion **30** is insulated, for example, by ion injection in the same manner as in the second Example. However, the coupling portion **30** does not have to be particularly isolated as in the first Example.

In the Example, the light emission region is limited to one place in the drive mesa **20**. Therefore, it is easy to control the optical mode of the emitted light to thereby lead to improvement of the coupling efficiency with an optical waveguide portion such as an optical fiber, in comparison with the case where light is emitted from two places in the drive mesa **20** and the control mesa **40** respectively.

Incidentally, other than the structure in which the control electrode per se covers the non-oxidized region **106B** of the control mesa **40**, a structure in which a material having light shielding properties against an oscillation wavelength is added or a dielectric multilayer film reflector etc. is added may be used as a unit for controlling the light emitted from the control mesa **40**.

FIG. **9** is a sectional view showing an example of the configuration of an optical transmission apparatus according to the Example. The optical transmission apparatus **400** includes a metal stem **420** mounted with an electronic component **410** having the VCSEL **10/10A/10B** formed therein. The stem **420** is covered with a hollow cap **430**. A ball lens **440** is fixed to the center of the cap **430**. A cylindrical housing **450** is further attached to the stem **420**. An optical fiber **470** is fixed to an end portion of the housing **450** through a ferrule **460**. Laser light modulated from the electronic component **410** is condensed by the ball lens **440**. The light is incident on the optical fiber **470** and transmitted therefrom. Incidentally, any other lens than the ball lens, such as a biconvex lens or a plano-convex lens, may be used.

Although preferable Examples of the invention have been described above in detail, the invention is not limited to the specific Examples. Various modifications or changes can be made without departing from the scope or spirit of the invention stated in Claims. Although VCSELs using AlGaAs compound semiconductors have been exemplarily described in the Examples, another VCSEL using a group III-V compound semiconductor layer may be used alternatively.

What is claimed is:

1. A vertical-cavity surface-emitting laser diode comprising:

a first resonator that has a plurality of semiconductor layers comprising a first current narrowing structure having a first conductive region and a first non-conductive region;

a first electrode that supplies electric power to drive the first resonator;

a second resonator that has a plurality of semiconductor layers comprising a second current narrowing structure having a second conductive region and a second non-conductive region and that is formed side by side with the first resonator, the second current narrowing structure being formed in same current narrowing layer as the layer where the first current narrowing structure is formed;

a coupling portion that couples the plurality of semiconductor layers in the first resonator with the plurality of semiconductor layers in the second resonator respectively; and

a second electrode that drives the second resonator to control a phase of light to be fed back to the first resonator side when the light propagated from the first resonator side to the second resonator side is fed back to the first resonator side, the second electrode being formed on the second resonator, wherein:

an equivalent refractive index of the coupling portion is smaller than an equivalent refractive index of each of the first resonator and the second resonator.

2. The vertical-cavity surface-emitting laser diode according to claim **1**, wherein the second electrode controls the

phase of the light so that the light can be fed back to the first resonator side with a reverse phase to the phase with which the light is propagated to the second resonator side.

3. The vertical-cavity surface-emitting laser diode according to claim 1, wherein a whole of an emission surface of the second resonator is covered with a light-shielding member.

4. The vertical-cavity surface-emitting laser diode according to claim 3, wherein the light-shielding member is the second electrode.

5. The vertical-cavity surface-emitting laser diode according to claim 1, wherein a distance between the first resonator and the second resonator and a width of the coupling portion are set at values with which high frequency characteristics can be improved more greatly than the first resonator to which the second resonator is not coupled.

6. The vertical-cavity surface-emitting laser diode according to claim 1, wherein electric resistance of the coupling portion is higher than electric resistance of each of the first resonator and the second resonator.

7. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the first resonator, the second resonator and the coupling portion have a multilayer film reflector including a laminate structure of high refractive index layers and low refractive index layers on an emission surface side of an active layer; and the multilayer reflector in the coupling portion is electrically insulated.

8. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the coupling portion comprises:

a third conductive region that connects the first conductive region and the second conductive region inside the current narrowing layer; and

a third non-conductive region that connects the first non-conductive region and the second non-conductive region inside the current narrowing layer.

9. An optical transmission apparatus comprising:

vertical-cavity surface-emitting laser diode according to claim 1; and

an application unit that applies a drive signal to the vertical-cavity surface-emitting laser diode.

10. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the second electrode drives the second resonator to control the phase of the light so that a frequency at which modulation sensitivity is −3 dB is improved in comparison to a case in which the first resonator is not coupled with the second resonator.

11. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the first resonator is driven by a first drive signal, and the second resonator is driven by a second drive signal different from the first drive signal during a time when the first resonator is being driven by the first drive signal.

12. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the first electrode is directly formed on the first resonator and is not formed on the second resonator, and the second electrode is directly formed on the second resonator and is not formed on the first resonator.

13. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the second electrode is formed on an end portion of the second resonator and is not formed on the coupling portion side of the second resonator.

14. The vertical-cavity surface-emitting laser diode according to claim 1, wherein the first electrode and the second electrode are formed on opposite ends of the first resonator and the second resonator, respectively, and are not formed on the coupling portion side of the first resonator and the second resonator.

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